Quantum Computing

James Amundson

51st Annual Users Meeting

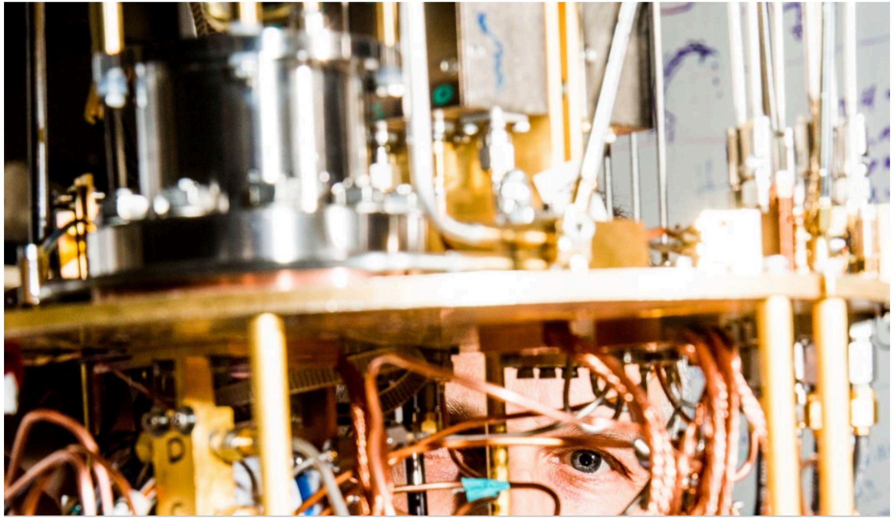
June 20, 2018

Quantum Computing Excitement

Nov. 13, 2017

The New York Times

Yale Professors Race Google and IBM to the First Quantum Computer



More Quantum Computing Excitement

October 16, 2017 THE WALL STREET JOURNAL.

Quantum Computing Excitement Has Reached the U.S. Congress

June 8, 2018

GIZMODO

Two Quantum Computing Bills Are Coming to Congress

Ryan F. Mandelbaum
6/08/18 5:26pm • Filed to: QUANTUM COMPUTING

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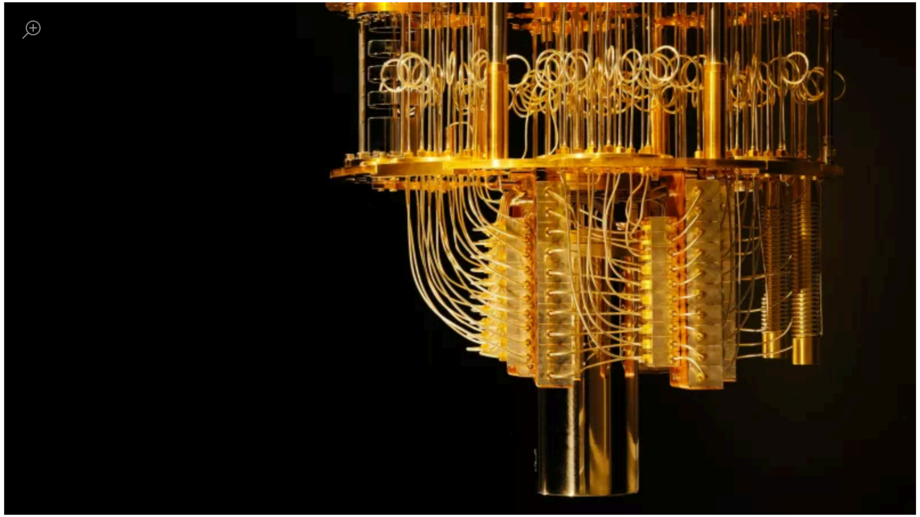


A dilution refrigerator from an IBM quantum computer.
Photo: IBM Research (Flickr)

Fermilab

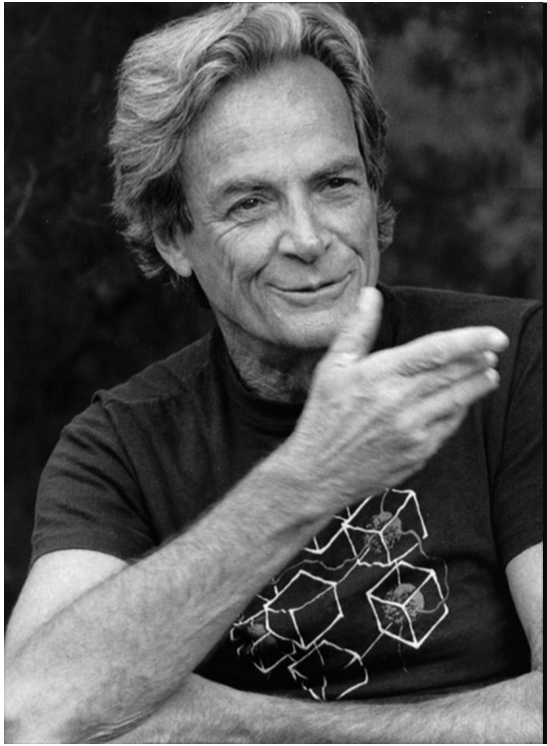
A Classical Take on Quantum Computing

Marcus Aurelius on Quantum Computing:

Anything in any way beautiful derives its beauty from itself and asks nothing beyond itself. Praise is no part of it, for nothing is made worse or better by praise.

A Quantum Take on Quantum Computing

Feynman was one of the originators of the idea…



Trying to find a computer simulation of physics seems to me to be an excellent program to follow out

. . .

the real use of it would be with quantum mechanics

. . .

Nature isn't classical . . . and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.

—1981

Quantum Information

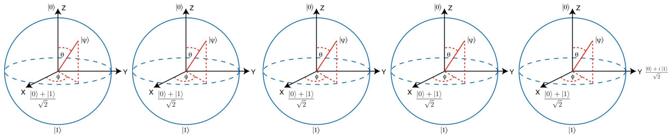
n classical 2-state systems: *n* bits of information

$b_1 \ldots b_n$

b_1 b_2 b_3 … b_n

n quantum 2-state systems: 2^n “bits” of information

$a_1 \ldots a_k$ where $k = 2^n$

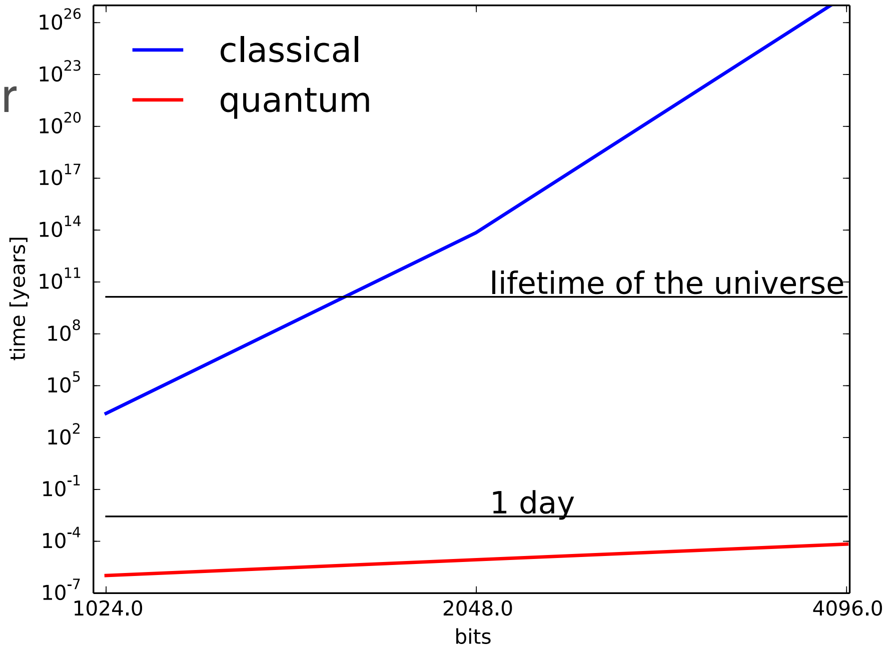


$$|\psi\rangle = a_1|0\ldots00\rangle + a_2|0\ldots01\rangle + a_3|0\ldots10\rangle + \ldots + a_k|1\ldots11\rangle$$

Where the Excitement Started

- Peter Shor: A general-purpose quantum computer could be used to efficiently factor large numbers
  - Shor's Algorithm (1994)
  - Resource estimates from LA-UR-97-4986 "Cryptography, Quantum Computation and Trapped Ions," Richard J. Hughes (1997)

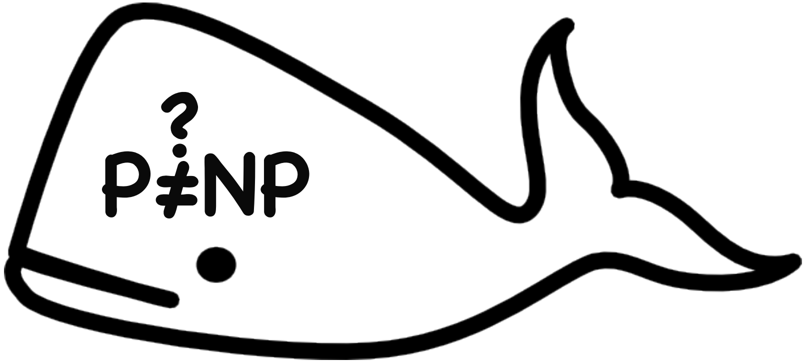
num size	1024 bits	2048 bits	4096 bits
qubits	5124	10244	20484
gates	$3x10^{10}$	$2x10^{11}$	$2x10^{12}$

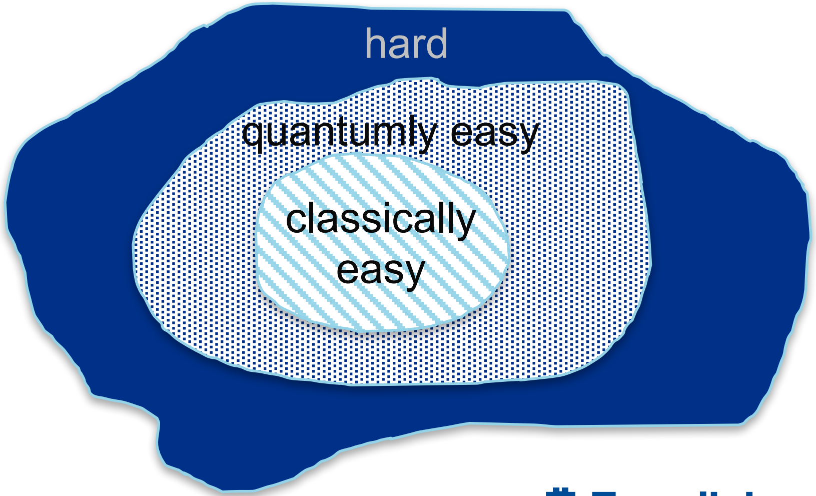


n.b. This is an old estimate; improvements have been made in the meantime.

Theoretical Computer Science

- Classical Computing
  - “Easy” problems can be solved in “polynomial time” (**P**)
  - “Hard” problems require “nondeterministic polynomial time” (**NP**)
    - Proving P ≠ NP is a great unsolved problem in computer science
- Quantum Computing
  - Some problems are easy in quantum computing, but hard in classical computing
  - Some problems appear to be hard either way



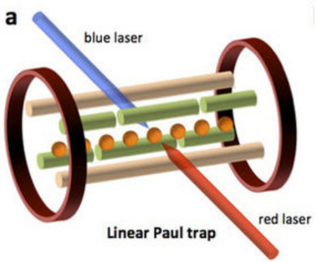


Quantum Algorithms

- Shor's Algorithm: factorization
  – Speedup: Superpolynomial
- Grover's Algorithm: search
  – Speedup: Polynomial
- Many more available at the Quantum Algorithm Zoo
  – https://math.nist.gov/quantum/zoo/

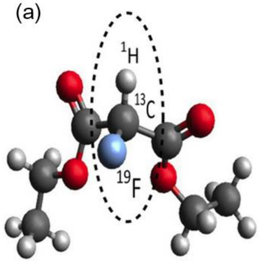
Current and Near-term Quantum Hardware

Ion trap



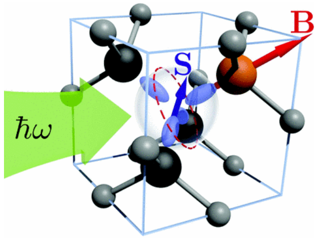
Scientific Reports 4, 3589 (2014)

NMR



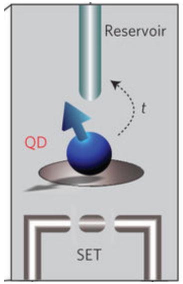
Sci. China Phys. Mech. Astron. 59:630302 (2016)

NV center



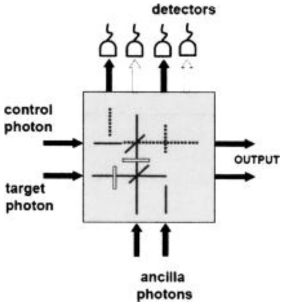
Phys. Rev. B 86, 125204 (2012)

Quantum dot



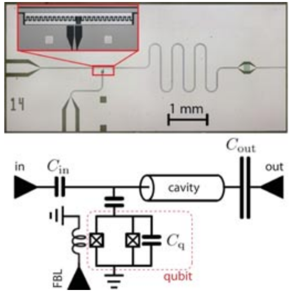
4 Nature Nanotechnology 9, 981–985 (2014)

Linear optical



J. Opt. Soc. Am. B, 24, 2, 209-213 (2007)

Superconducting



Ann. Phys. (Berlin) 525, 6, 395–412 (2013)

… many more

- Thanks to Andy Li
  - Fermilab Scientific Computing Division's first quantum computing postdoc!

Current Commercial Quantum Computing Efforts

- Many companies have announced that they have produced small quantum computers in the 5-72 qubit range
  - Google
  - IBM
  - Intel
  - Rigetti
  - IonQ
  - Other companies…
  - Academic efforts…
  - D-Wave
    - Quantum Annealing machine
      - Subject of a much longer talk

Counting Qubits is Only the Beginning

- The number of gates that can be applied before losing quantum coherence is the limiting factor for most applications
  - Current estimates run few – thousand
  - Not all gates are the same
    - The real world is complicated
- IBM has a paper proposing a definition of “Quantum Volume”
  - Everyone else seems to dislike the particular definition
  - The machines with the largest number of qubits are unlikely to have the largest quantum volume

From the earlier factoring estimate

num bits	1024 bits	2048 bits	4096 bits
qubits	5124	10244	20484
gates	3×10^{10}	2×10^{11}	2×10^{12}

- “Logical qubits” incorporating error correction are the goal
  - Probably require ~1000 qubits per logical qubit
    - Minimum fidelity for constituent qubits is the current goalpost

Fermilab Quantum Efforts

- Fermilab has a mixture of on-going and proposed work in quantum computing in four areas:
  - Quantum Computing for Fermilab Science
  - HEP Technology for Quantum Computing
  - Quantum Technology for HEP Experiments
  - Quantum Networking

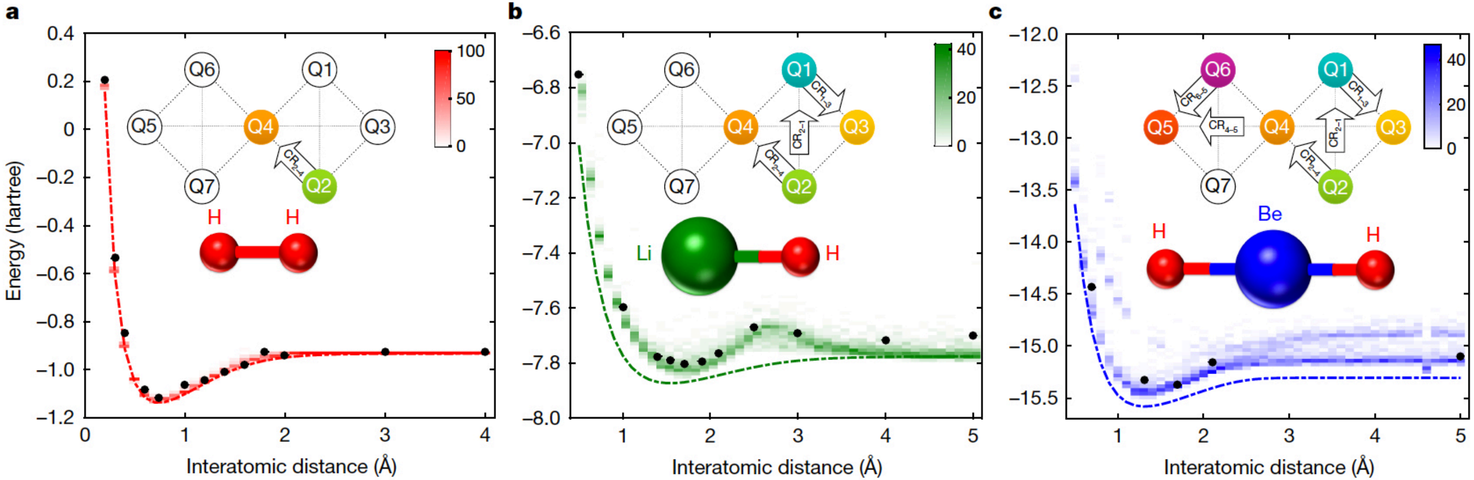
Quantum Computing for Fermilab Science

- Quantum Computing will require the sort of infrastructure Fermilab already provides for classical computing
  - HEPCloud will extend to Quantum Computing
  - On-going testbed effort in collaboration with Google
    - Partially funded by Fermilab LDRD
- Three promising areas for quantum applications in the HEP realm
  - Optimization
    - Area under active investigation in the quantum world
    - NP-hard problems
    - Quantum Approximate Optimization Algorithm (QAOA)
      - Farhi, Goldstone and Gutmann
  - Machine Learning
    - Computationally intensive
    - Also under active investigation in the quantum world
  - Quantum Simulation
    - Good reason to believe that quantum systems should be well-suited to quantum computation

Fermilab Quantum Application Efforts

- Quantum Optimization and Machine Learning
  - Proposed work by Gabe Purdue, et al.
- Quantum Information Science for Applied Quantum Field Theory
  - Marcela Carena, et al., including y.t. (yours truly)
  - Scientific Computing Division/Theory Department collaboration
    - Also includes University of Washington and California Institute of Technology
  - First effort: Digital quantum computation of fermion-boson interacting systems

Successful Quantum Simulation



- Quantum Chemistry has the first big successes in quantum simulation.
- GitHub has a project for general simulations of interacting fermions.
- However, interesting HEP systems, e.g., QCD, also require boson-fermion interactions.

OpenFermion

https://github.com/quantumlib/OpenFermion

Digital quantum computation of fermion-boson interacting systems

- Previous encoding schemes for bosons on quantum computers had errors of $O(n_{occupation}/n_{qubits})$
- Alexandru Macridin, Panagiotis Spentzouris, James Amundson, Roni Harnik
  - Digital quantum computation of fermion-boson interacting systems
    - **arXiv:1805.09928**
    - Accurate and efficient simulation of fermion-boson systems; simple enough for use on near-term hardware
  - Electron-Phonon Systems on a Universal Quantum Computer
    - **arXiv:1802.07347**
    - First application was to polarons – electron dressed by phonons. Cross-disciplinary interest.

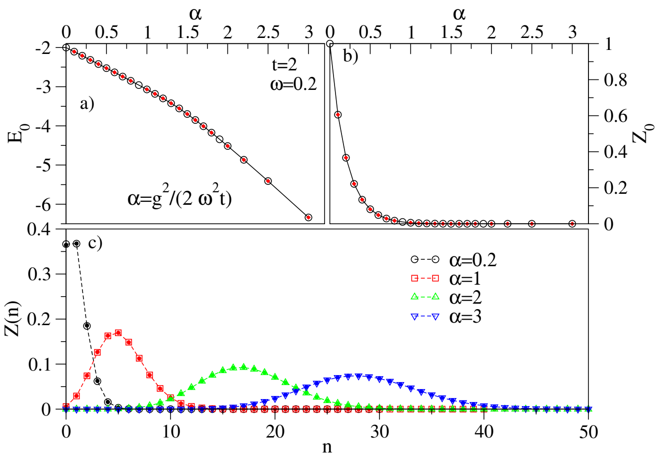


FIG. 4. $n_x = 6$ qubits per HO. The energy (a) and quasiparticle weight (b) for the 2-site Holstein polaron versus coupling strength. (c) The phonon number distribution for different couplings. The open (full) symbols are computed using exact diagonalization (QPE algorithm on a quantum simulator).

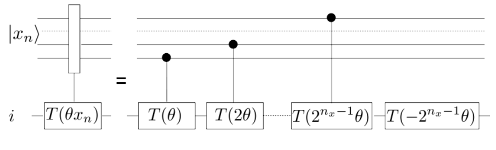
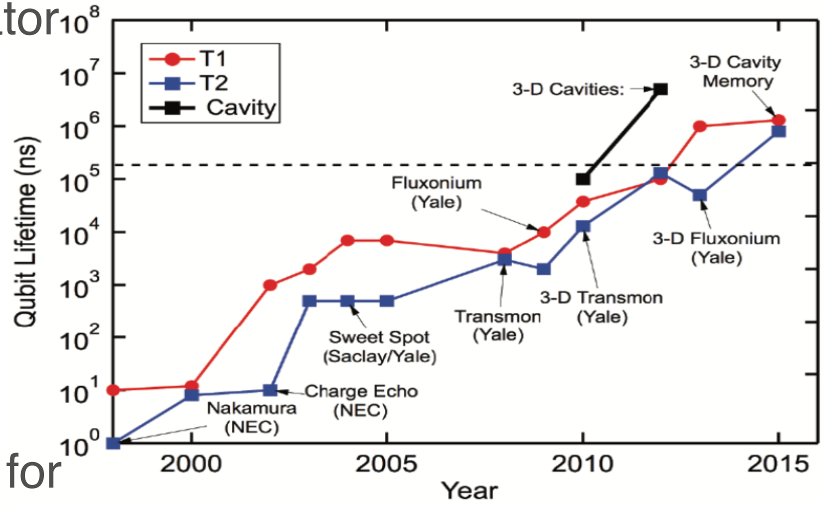


FIG. 3. Circuit for $\exp(-i\theta c_i^\dagger c_i \tilde{X}_n)|i\rangle \otimes |x_n\rangle$. The phase shift angle is $\theta(x_n - N_x/2) = \theta \sum_{r=0}^{n_x-1} x_n^r 2^r - \theta 2^{n_x-1}$, where $\{x_n^r\}_{r=\overline{0,n_x-1}}$ take binary values.

HEP Technology for Quantum Computing

SRF resonators

- Ultra-High Q Superconducting Accelerator Cavities for Orders of Magnitude Improvement in Qubit Coherence
  - Alex Romanenko, et al.

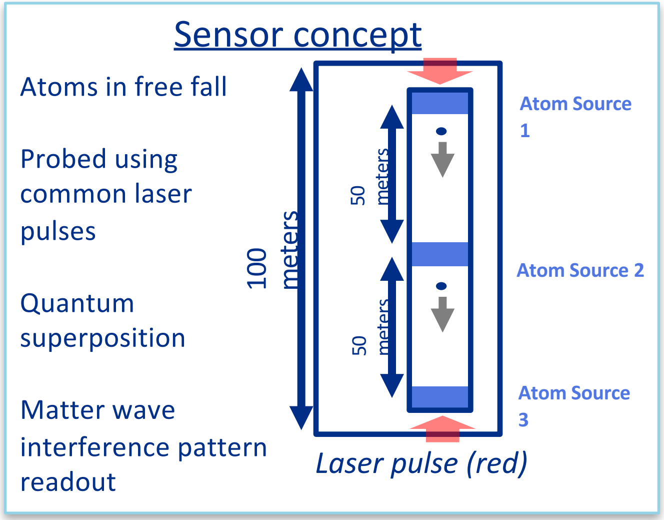


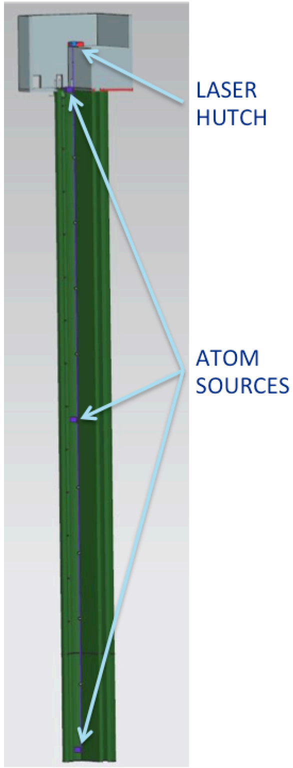
- Novel Cold Instrumentation Electronics for Quantum Information Systems
  - Davide Braga, et al.

Fermilab

Quantum Technology for HEP Experiments

- Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)
  - Robert Plunkett, et al.
- Skipper-CCD: new single photon sensor for quantum imaging
  - Juan Estrada, et al.
- Quantum Metrology Techniques for Axion Dark Matter Detection
  - Aaron Chou, et al.





CAD model of detector in 100-meter MINOS shaft)

Quantum Networking

- Quantum Networking is outside the scope of this talk
  - We are working on it at Fermilab, in collaboration with the California Institute of Technology
  - Quantum Communication Channels for Fundamental Physics
    - Maria Spiropulu, et al. (California Institute of Technology)

Conclusions

- Quantum computing holds the promise of remarkable new computational capabilities
  – The future is not here yet
    - … but we are getting there
- Fermilab has quantum computing efforts on many fronts
  – Quantum Applications
  – HEP technology for QC
  – QC technology for HEP experiments
  – Quantum Networking